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Study on Upgrading Power of 600MWe PWR with Annular Fuel

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ABSTRACT*: One of the motivations of the annular fuel R&D in China Institute of Atomic Energy (CIAE) is to upgrade the power density of current PWR NPPs. To examine the feasibility of upgrading power density and the potential safety margin of using annular fuel in PWRs, QinShan-II (600MWe PWR NPP) core with annular fuel is conceptually designed and analyzed, the results show that the power of QinShan-II NPP can be upgraded to 900MWe by using annular fuel while maintaining the safety margin.*

KEYWORDS*: annular fuel, PWR, power upgrade*

I. INTRODUCTION

Annular fuel, which is consists of two claddings and annular pellets, is proposed to be used to increase power density while maintaining or improving safety margins comparable to currently operating LWR plants, and is considered as one of the main trends in the high performance LWR fuel development [1]. The Fig.1 shows the schematic of an annular fuel rod with two coolant channels. Fig.2 shows a schematic of a typical annular fuel assembly (13×13 array size).

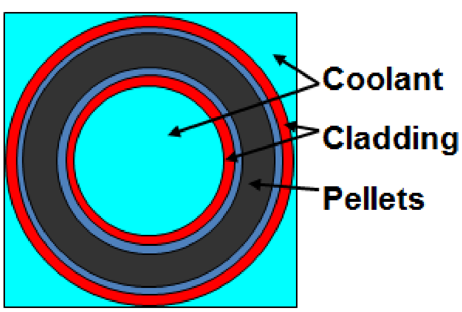


Fig.1 Schematic of an annular fuel rod

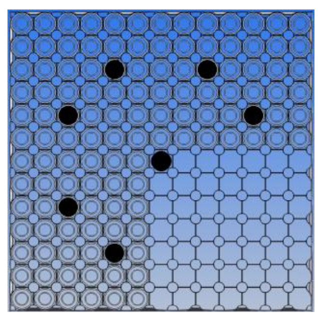


Fig.2 schematic of annular fuel assembly (13×13 array)

One of the motivations of the annular fuel R&D in CIAE is to upgrade the power density of current PWR NPPs [2]. It's necessary to do a conceptual design of reactor core and fuel assembly based on a reference PWR to make sure the feasibility and to examine the potential safety margin of reactor with annular fuel. QinShan-II NPP, which is 600MWe for 2 loops PWR, is selected as the base case for the study. Table I summarized the design data of the reference PWR core.

In this work, QinShan-II core is conceptual designed for increasing 50% power density with replacing all solid fuel assemblies by annular fuel assemblies. In the core design, core inlet temperature, core pressure drop are kept fixed with the reference values of base case with solid fuel, while the coolant flow rate is increased to accommodate the additional 50%

energy. Meanwhile, the structure of the annular fuel assembly is redesigned to meet the safety requirements, which are mainly concerned with reactor physics, mechanical, fuel irradiation performance, reactor safety and thermal-hydraulics.

TABLE I. General design data of QinShan-II NPP core

Reactor type	PWR	Core thermal power	1930MW$_{th}$
Core inlet temperature	293.4℃	Core outlet temperature	329.8℃
Fuel assembly type	AFA-3G	Number of fuel assembly	121
Active core length	3.658m	Average linear heat rate	16.09 kW/m
Bypass fraction	4.3% (Max 6.5%)	Coolant pressure	15.5MPa
Average core pressure drop	0.128 MPa	Average mass flux	46640m^3/h

II. DESIGN OF ANNULAR FUEL ASSEMBLY AND CORE

The basis of annular fuel assembly design is using the annular fuel rod instead of solid fuel rod while maintaining the shape and dimensions of the fuel assembly. Comparing the thermal-hydraulic analysis results among different array sizes, mainly MDNBR and core pressure drop results, 13×13 annular fuel assembly, with 160 fuel rods, 8 control rods and 1 instrument tube, is chosen to instead of original 17×17 solid fuel assembly. Fig.3 shows the core pressure drop results for different arrays, and Fig.4 shows the MDNBR results as a function of array sizes.

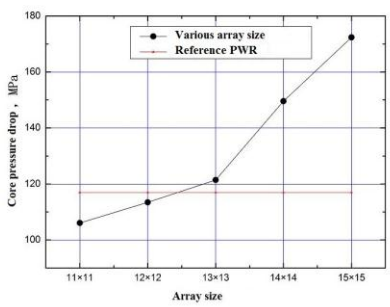


Fig.3 Core pressure drop for different arrays

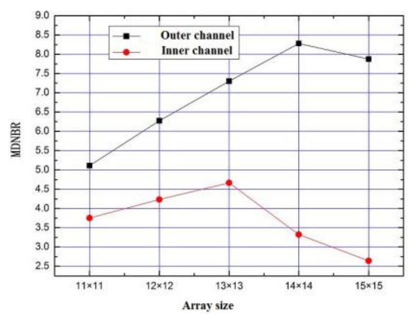


Fig.4 MDNBR as a function of array sizes

The annular core design followed the existing industrial 3-batch core for a 12-month cycle, while maintaining the maximum boron concentration, radial pin power factor and hot spot factor as same as the reference core requirements. The loading 121 assemblies are subdivided into seven different groups depended on the enrichment of ^{235}U and number of burnable poison rods in which the weight percentage of Ga_2O_3 is 5%. The 900MWe core is consisted of 40 assemblies with enrichment of ^{235}U 4.9%, 40 assemblies with enrichment of ^{235}U 4.5% and 41 assemblies with enrichment of ^{235}U 4.1%. Table II shows these seven groups used in the annular core design and analysis and Fig.5 shows the schematic of annular core design.

TABLE II. Annular fuel assemblies used in core design

Group	Symbol and color of assembly	Enrichment of 235U in assembly	Burnable poison rod numbers
1		4.1	0
2	32	4.1	32
3		4.5	0
4	32	4.5	32

5	40	4.5	40
6		4.9	0
7	32	4.9	32

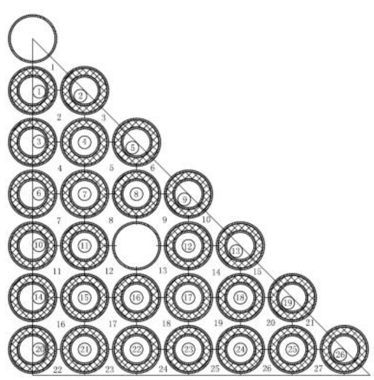
	1	2	3	4	5	6	7	8	9	10	11	12	13
A													
B					32		32		32				
C				32		40		40		32			
D			32		40		40		40		32		
E		32		40		32		32		40		32	
F			40		32		32		32		40		
G		32		40		32		32		40		32	
H			40		32		32		32		40		
J		32		40		32		32		40		32	
K			32		40		40		40		32		
L				32		40		40		32			
M					32		32		32				
N													

Fig.5 Schematic of annular fuel core design (1st cycle)

III. ANALYSIS RESULTS

III.A Thermal Hydraulic results [3]

SAAF (Sub-channel Analyzer for Annular Fuel) code, developed by CIAE based on COBRA code, has been used for core and assembly thermal hydraulic study. In a whole core model, all rods and channels are modeled and a sub-channel analysis scheme is used. The numbering scheme of channels and rods in the hot fuel assembly with 1/8 symmetry is shown in Fig.6. The power distribution in the hot assembly of the 13×13 configuration was list in Table III.



1, 2, 3……is the numbers of outer channels
① ,②, ③……is the numbers of inner channels and fuel pins

Fig.6 Numbering scheme of channels and rods in the hot fuel assembly with 1/8 symmetry

TABLE III Factor of radial and axial power distribution

Radial power factor							
Pin number	1	2	3	4	5	6	7
Radial factor	1.085	1.026	0.999	1.011	1.024	1.007	1.027
Pin number	8	9	10	11	12	13	14
Radial factor	1.071	1.049	1.005	1.057	1.044	0.961	0.981
Pin number	15	16	17	18	19	20	21
Radial factor	0.999	1.033	0.976	0.939	0.92	0.979	0.975
Pin number	22	23	24	25	26		
Radial factor	0.971	0.955	0.934	0.921	0.926		
Axial power factor							
Node Number	1	2	3	4	5	6	7
Axial factor	0.565	0.918	1.154	1.305	1.405	1.484	1.546
Node Number	8	9	10	11	12	13	14
Axial factor	1.591	1.631	1.655	1.669	1.668	1.663	1.645
Node Number	15	16	17	18	19	20	21
Axial factor	1.612	1.575	1.518	1.444	1.36	1.261	1.141
Node Number	22	23	24				
Axial factor	0.981	0.763	0.479				

Pressure drop: The distribution of the average pressure drop along the axial distance is similar for the inner channel and outer channel, see Fig.7.

MDNBR: the minimum DNBR (MDNBR) occurred in number 1 coolant channel as shown in Figure 6. The distribution of MDNBR of the inner and outer channels along the axial distribution is shown in Fig.8. The MDNBR in inner hot channel is larger than the outer hot channel, because there are grids in outer channels so the flow resistances in outer channels are greater than inner channels with the same mass flow. The effect of the flow resistance will be more coolant squeezed into the inner channel so that the inner channels can be cooled better. The MDNBRs in inner and outer channels are relatively close, and much larger than the 1.8 limit, the security margin is larger than solid fuel assembly.

Temperature of cladding and Coolant: The distribution of the surface temperatures of the inner and outer claddings with the number 1 are shown in Fig.9. It can be seen that in the steady state operation, the surface temperature of the cladding is less than the temperature limit of 350℃. The distribution of the coolant temperatures along the axial distance of outer and inner channels is shown in Fig.10.

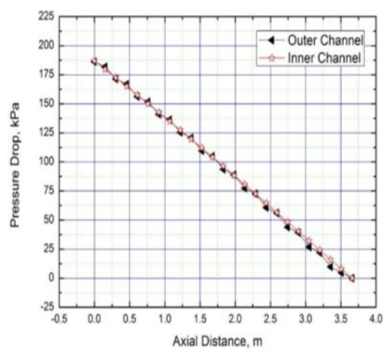


Fig.7 Pressure drop in the hot inner and outer channels

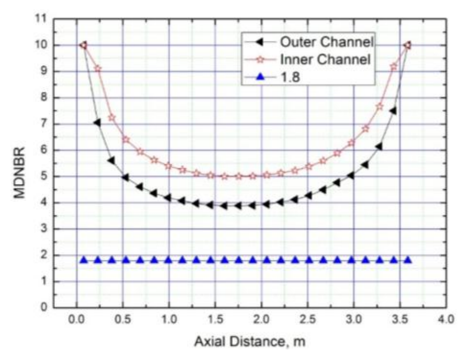


Fig.8 MDNBR in the hot inner and outer channels

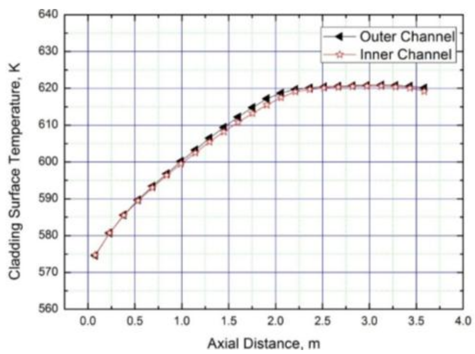


Fig.9 Cladding surface temperatures in the hot inner and outer channels

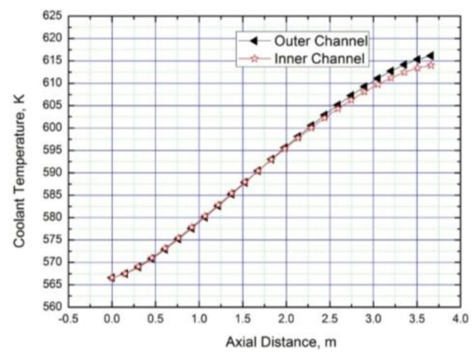


Fig.10 Coolant temperatures in the hot inner and outer channels

III.B Physics Results [4]

The annular fuel core physics analysis is mainly performed by the FMP code which is developed for LWR core physics calculations by CIAE.

Core critical boron concentration at BOC is 1270 ppm. The cycle length is 305.6EFPDs which meet the 12-month cycle requirement. At the EOC, the core average burnup is 15906MWd/tU which is less than the 22500 MWd/tU on which the core K_{eff}>1.0, like Fig.11 shown. The moderator temperature coefficient is negative throughout the cycle, like Fig.12 shown. It is feasible to design an annular core reactor for 150% power based on the existing 600WMe PWR core.

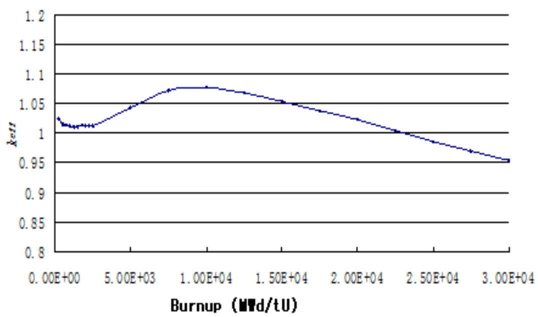


Fig.11 K_{eff} at different burnup of the annular core

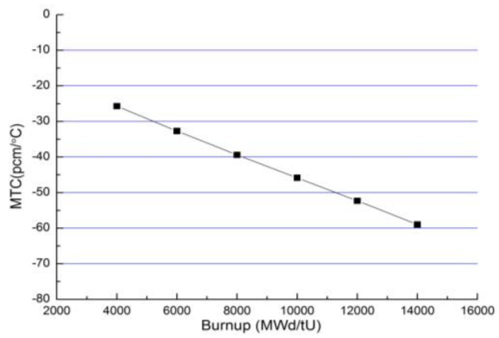


Fig.12 MTC at different burnup of the annular core

III.C Fuel Performance Results [5]

AFPAC 1.0 (Annular Fuel Performance Analysis Code) has been used to analyze the fuel rod’s behavior under steady irradiation condition for 100% and 150% power density level comparable to QinShan-II NPP, while METEOR 1.9 code has been used to analyze solid fuel rod’s steady behavior on 100% power level. The main results are summarized in Table IV.

Fig.13 shows the annular rod’s temperature distribution vs. radius position. For the 100% power level, the average linear heating rate is 27.25kW/m, the peaking temperature of pellet is 717.19K, while for the 150% power level, the average linear heating rate is 40.88kW/m. the peaking temperature of the pellet is 780.50K. The average temperature of cladding under 150% power level case is less than 100% power level case, the reason is mainly mass flow rate is 50% higher than the former one.

The results show that: 1) annular fuel rod has a better in-pile performance than solid fuel rod, including lower temperature, less FGR, less inner pressure and less deformation; 2) even operated in 150% power level, the main parameters concerned with irradiation behavior meet the safety requirement of current operating PWRs.

TABLE IV Fuel performance analysis results

Case	Peak Temperature	FGR at EOL	Inner Pressure	Pellet maximum deformation	Inner Cladding maximum deformation	Outer Cladding maximum deformation
Solid 100%	1363.15K	0.83%	5.17MPa	1.67%	/	0.08%
Annular 100%	717.19K	0.058%	4.21 MPa	0.4%	0.2%	0.0%
Annular 150%	780.50K	0.088%	4.41 MPa	0.6%	0.2%	0.0%

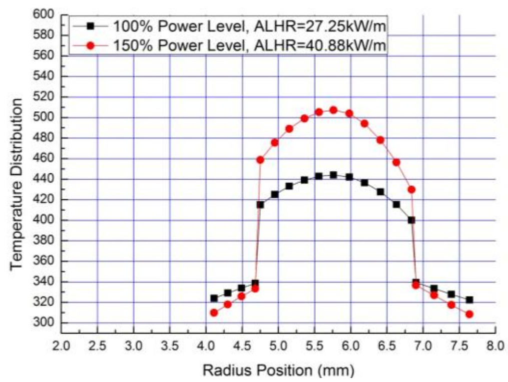


Fig.13 Annular fuel rod's temperature radial distribution at different power level

III.D Reactor Safety Results

The new models based on RELAP5 MOD3.2 have been developed to study the safety of QinShan-II NPP with annular fuel. The Loss of Flow Accident (LOFA), Main Steam Line Break (MSLB), Large Break Loss of Coolant Accident (LBLOCA) and Rod Ejection Accident (REA) are analyzed for 100% power level with solid and annular fuel, and 150% power level with annular fuel. Figure 14 shows the nodalization of QinShan-II NPP base on the REALP 5 MOD3.2 code input requirements.

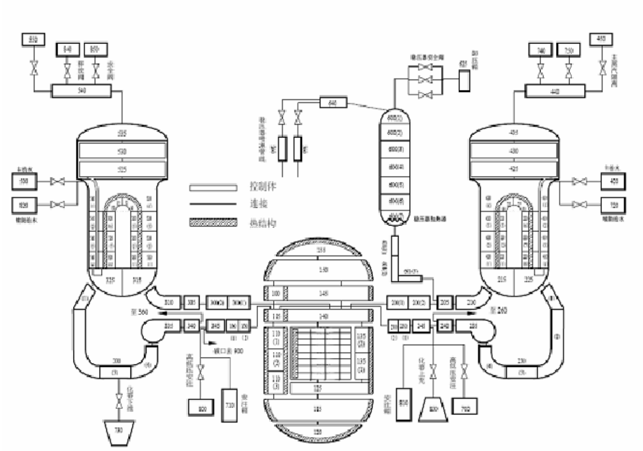


Fig.14 Nodalization of Qinshan-II NPP

The main results of the analysis are shown in Table V, it's clearly indicates that the safety of annular core is better than current solid core. Even operating under the 150% power level, the peaking temperature of cladding of annular fuel rod, 669.46K, is much less than the one of solid fuel operating under 100% power level.

TABLE V Safety analysis results for QinShan-II NPP loaded with annular and solid fuel

	Solid fuel 100% power	Annular fuel 100% power	Annular fuel 150% power
LOFA	PTC 1010.8K	—	PTC 669.46 K
MSLB	PTC 671K	PTC 630K	PTC 653K
LBLOCA	PTC 1335 K	PTC 837K	PTC 1137K
REA	Average enthalpy in pellets 102cal/g	Average enthalpy in pellets 61cal/g	Average enthalpy in pellets 72cal/g

IV. CONCLUSION

Current operating QinShan-II NPP core is selected as a reference case for examining the feasibility of power upgrading by using annular fuel. The analysis results, which mainly include reactor physics, thermal-hydraulic, nuclear safety and fuel steady irradiation performance, shows the feasibility and advantage of using annular fuel in current PWR NPPs to upgrade the power.

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